Single Spin Asymmetries: from JLab12 to EIC

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- Introduction
- Semi-Inclusive processes and TMD distributions
- Hard exclusive processes and GPDs
- Summary

Single-Spin Asymmetries Workshop, BNL June 1-3, 2005

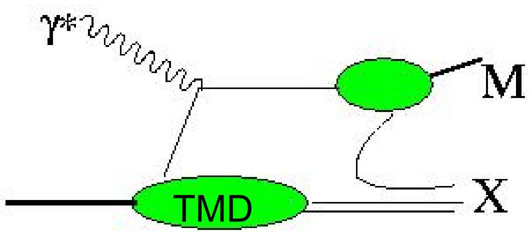
*) In collaboration with V. Burkert and L. Elouadrhiri

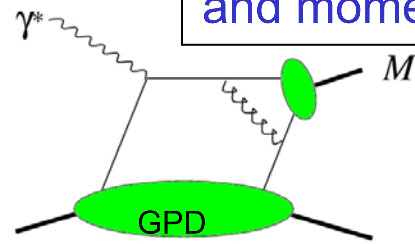
$W_p^u(x,\mathbf{k},\mathbf{r})$ “Parent” Wigner distributions

Probability to find a quark **u** in a nucleon **P** with a certain polarization in a position **r** and momentum **k**

d^3r

d^2k_T (FT)





TMD PDFs $f_p^u(x,k_T)$,

GPDs $H_p^u(x,\xi,t)$..

$f_1^q(x,\mathbf{k}_\perp)$ g_1^q $f_{1T}^{\perp q}$ g_{1T}^q

h_1^q $h_{1T}^{\perp q}$ $h_{1L}^{\perp q}$ $h_1^{\perp q}$

$H^q(x,\xi,t)$ $\tilde{H}^q$ E^q $\tilde{E}^q$

H_T^q $\tilde{H}_T^q$ E_T^q $\tilde{E}_T^q$

Measure momentum transfer to quark

d^2k_T

$\xi=0,t=0$

dx

Measure momentum transfer to target

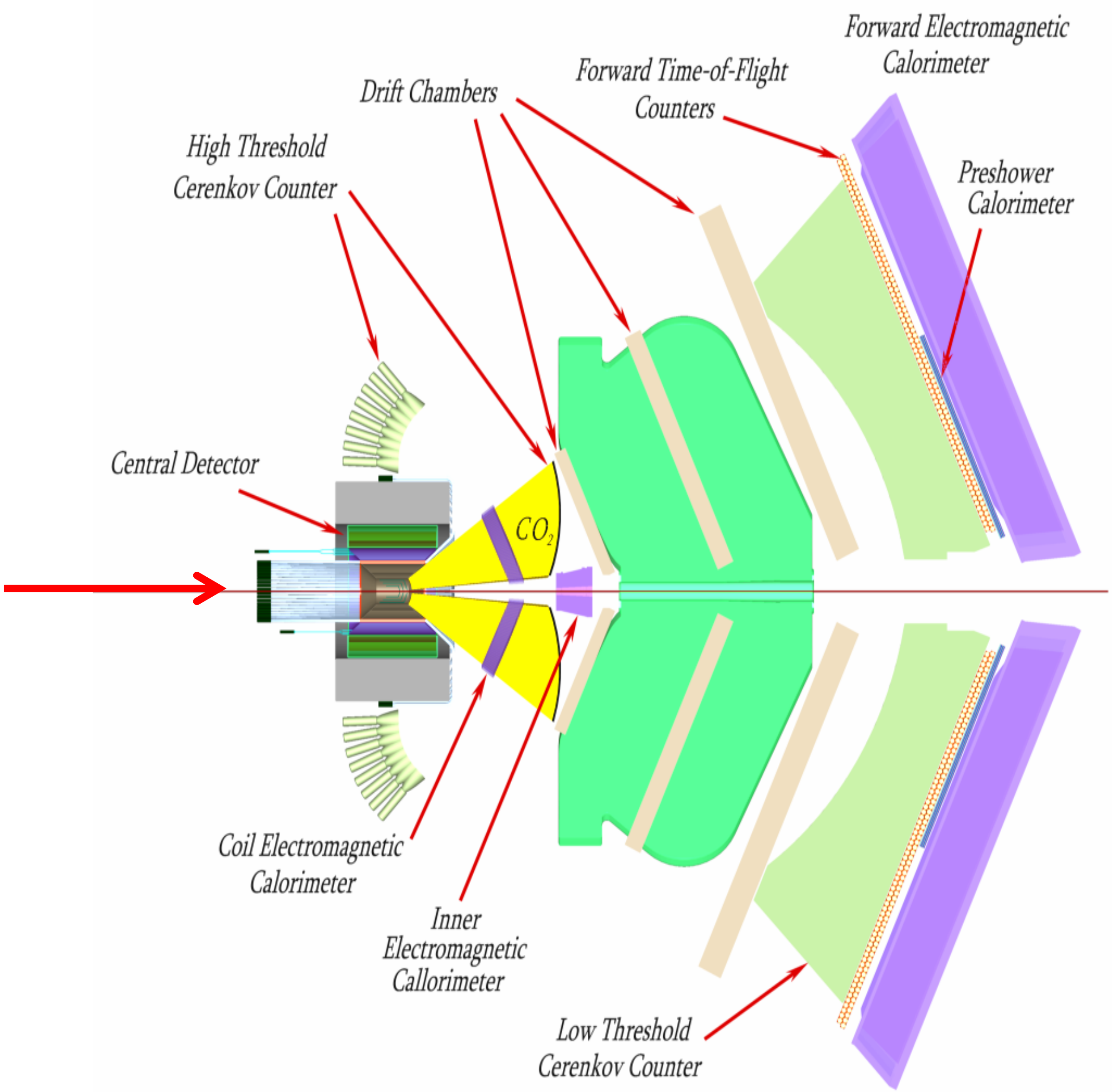
PDFs $f_p^u(x)$, g_1, h_1

FFs $F_{1p}^u(t)$,$F_{2p}^u(t)$..

k_T-integrated PDFs same in exclusive and semi-inclusive analysis

Analysis of SIDIS and DVMP are complementary

CLAS12

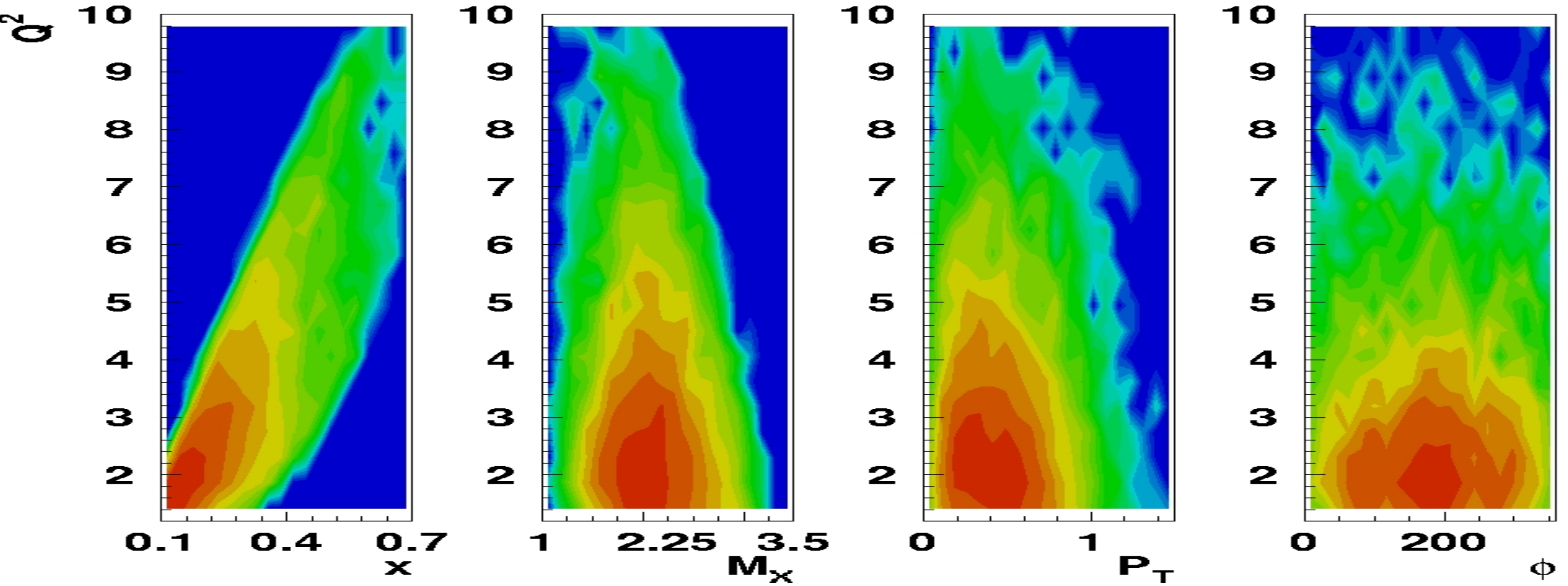


High luminosity polarized CW beam

Wide physics acceptance (exclusive, semi-inclusive current and target fragmentation)

Wide geometric acceptance

ep→e'πX: kinematic coverage at 11 GeV



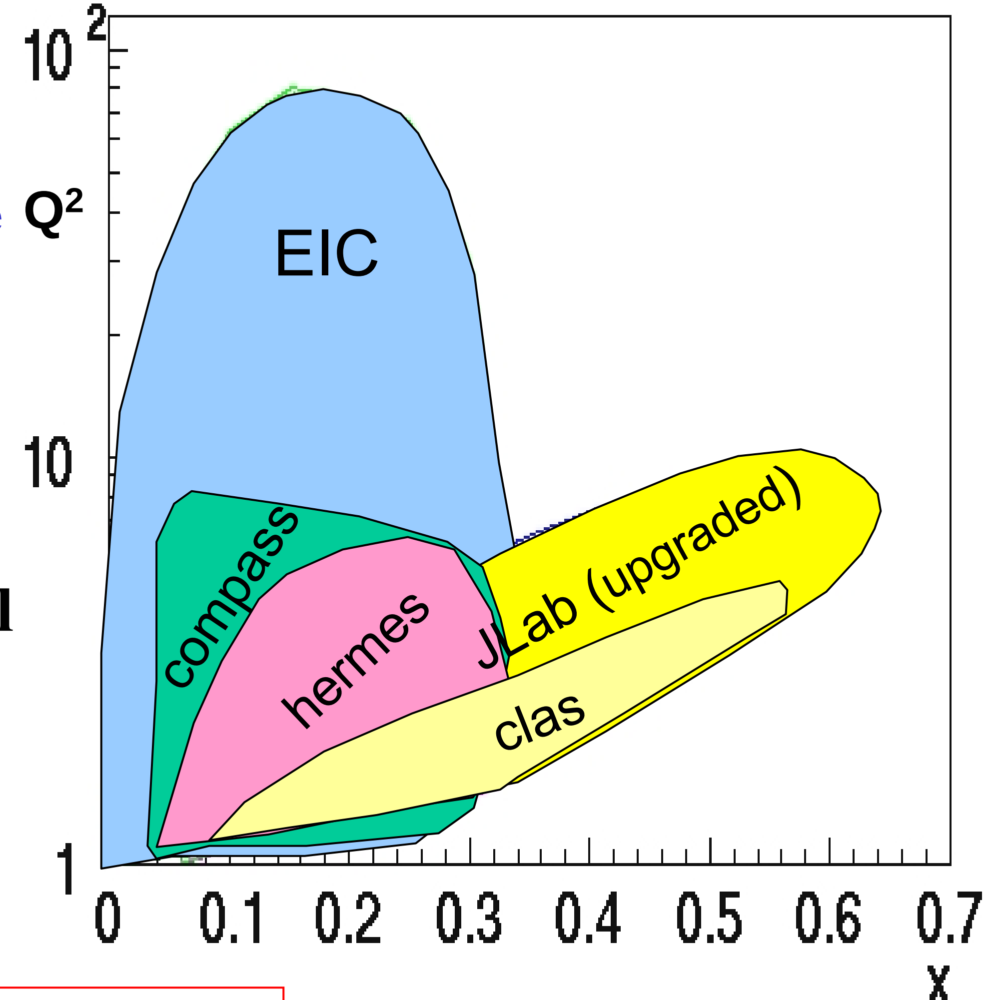
➢Acceptance in Q^2,M_x,P_T gained with high luminosity and energy upgrade (at 6GeV M_x<2.5GeV, Q^2<4.5GeV^2, P_T<1GeV)

➢test factorization in a wide kinematical range
➢study the transition between the non-perturbative and perturbative regimes of QCD
➢measure PDFs and study higher twists

EIC

- Collider measurements, requiring high luminosity ($L \sim 10^{34}$-$10^{35} cm^{-2}\ sec^{-1}$), and wide coverage, will vastly increase the kinematics and the scope of observables.

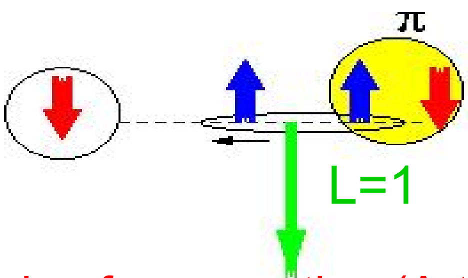
    - Large Q^2 may be crucial for precision studies of hard exclusive meson production.



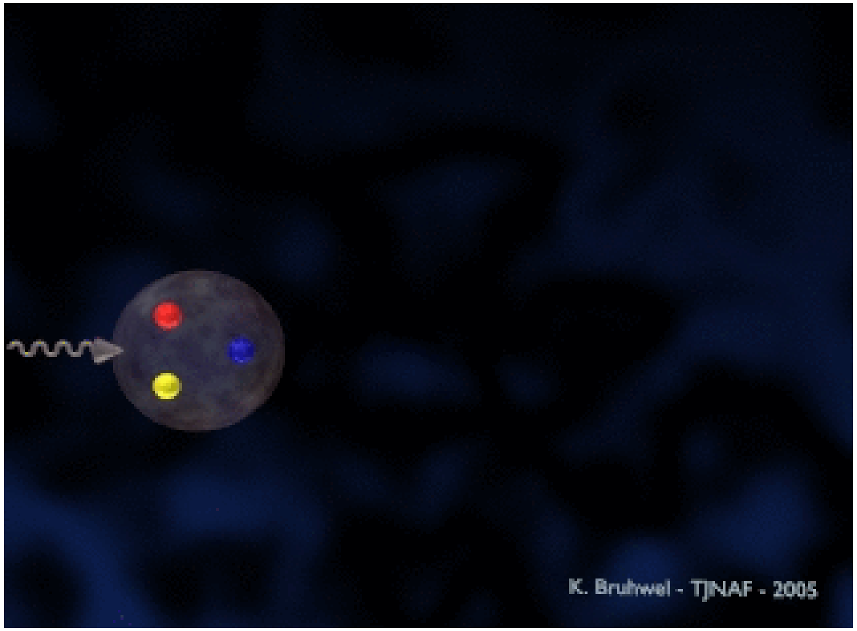
EIC: large acceptance high luminosity

Mechanisms for SSA

Collins Fragmentation

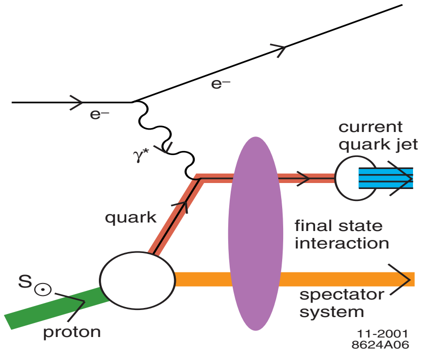


String fragmenation (Artru)

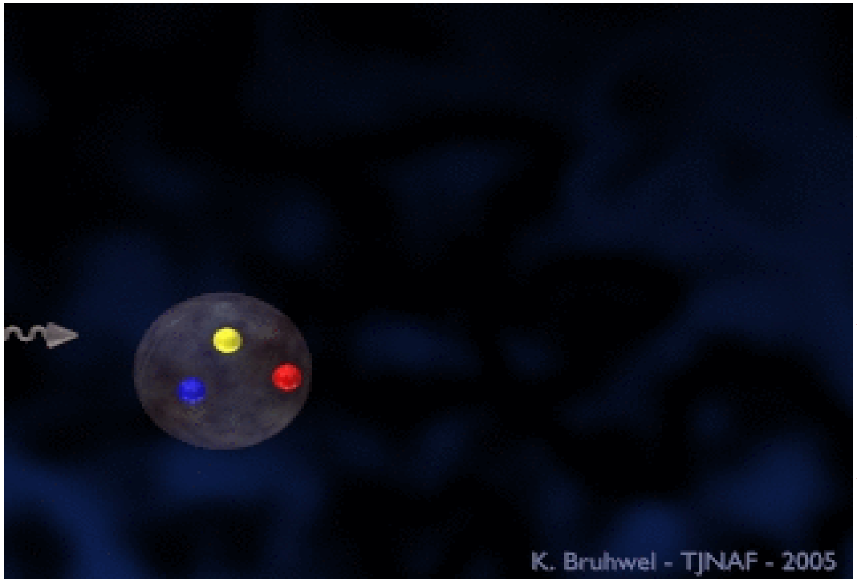


- L/R SSA generated in fragmentation
- Unfavored SSA with opposite sign
- No effect in target fragmenation

Sivers Distribution



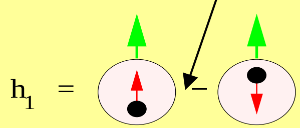
FSI (Brodsky et al.)



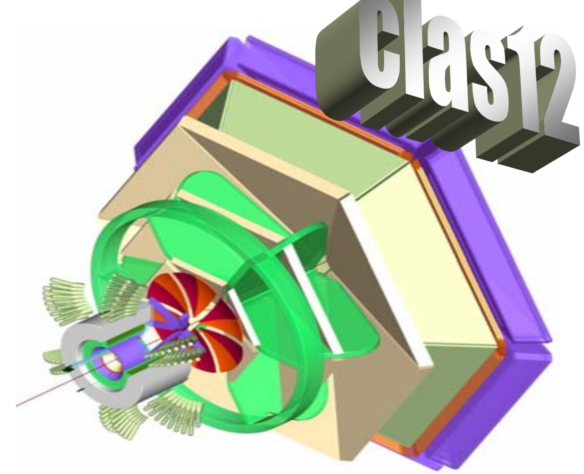
- L/R SSA generated in distribution
- Hadrons from struck quark have the same sign SSA
- Opposite effect in target fragmentation

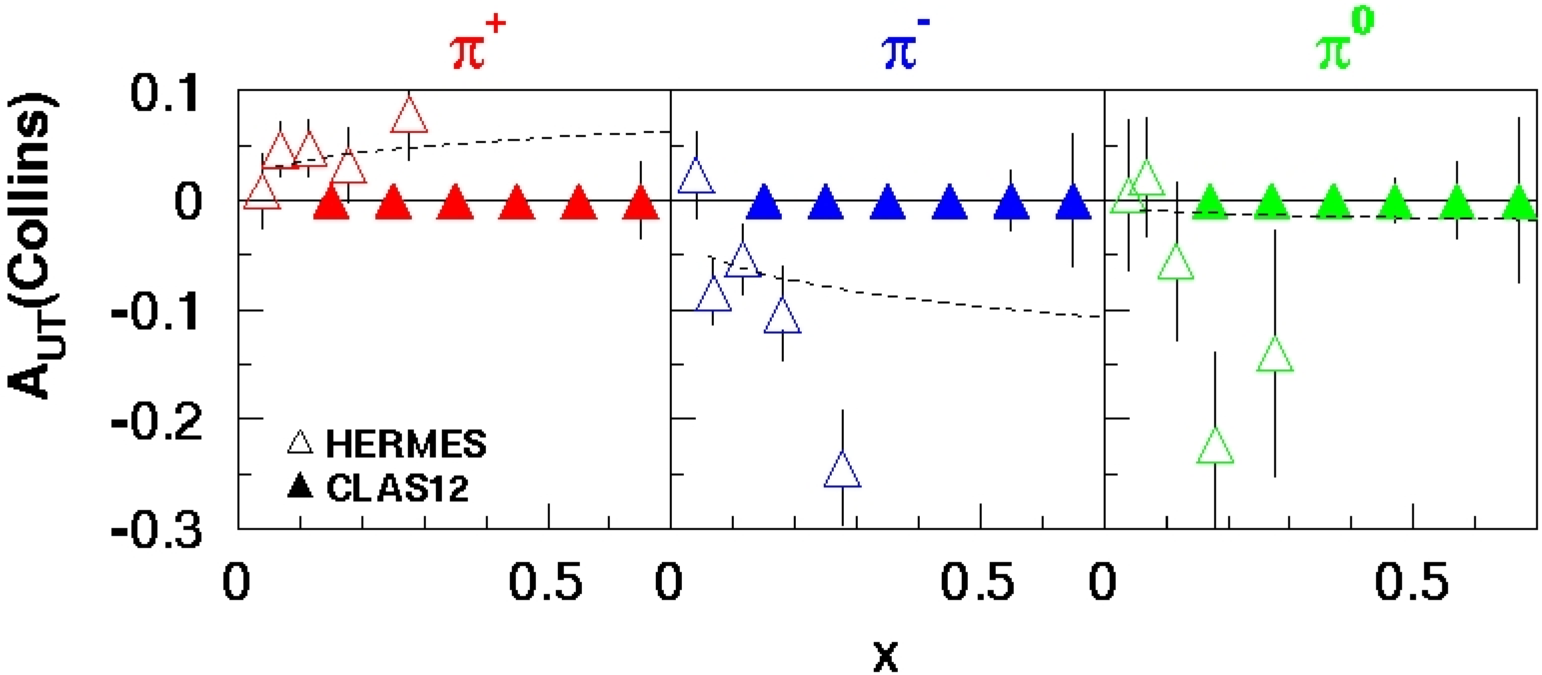
Collins Effect

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$



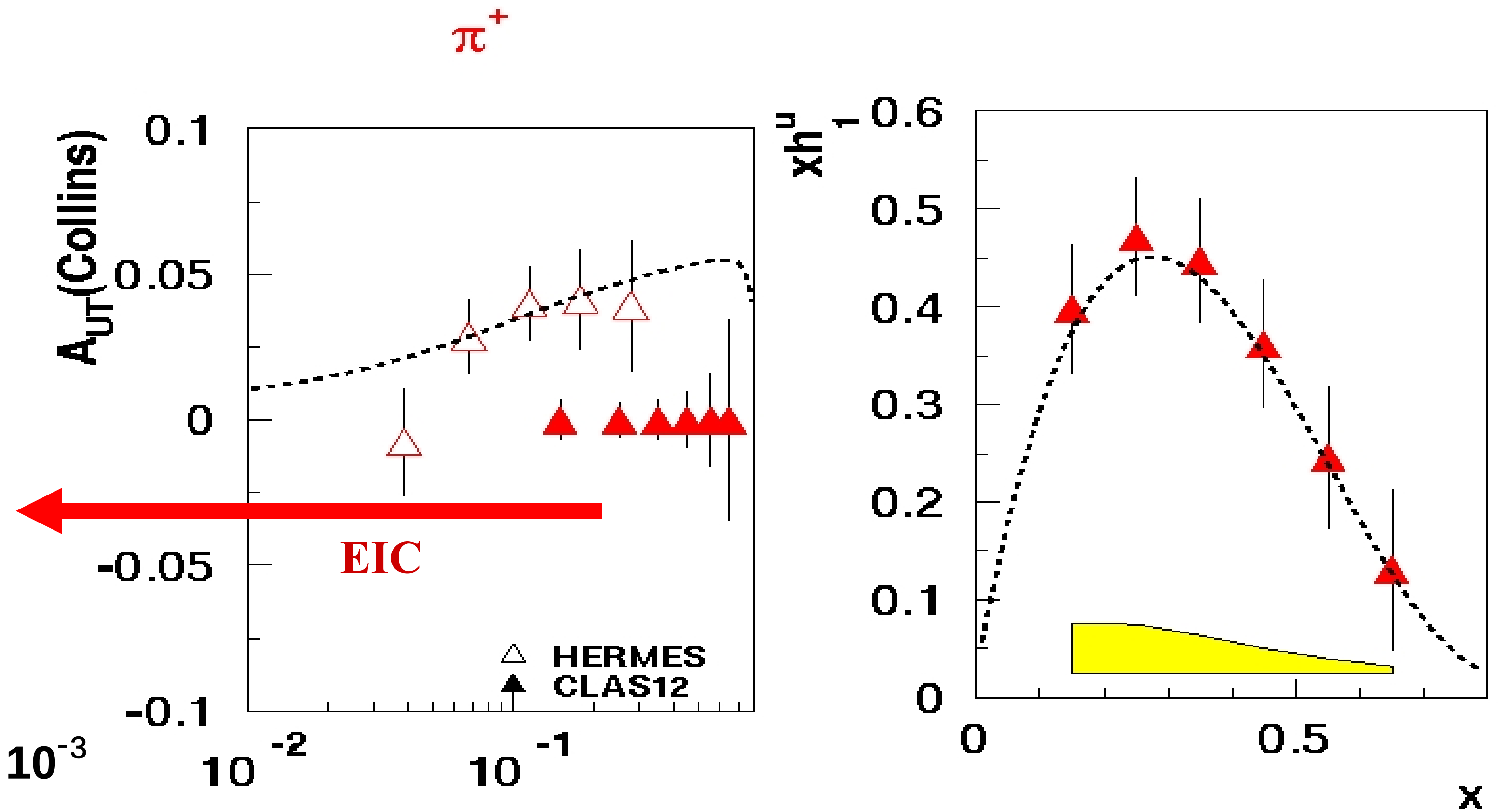
$$\sigma_{UT}^{\text{Collins}} \sim (1-y)\, h_1 H_1^{\perp}$$





Study the Collins fragmentation for all 3 pions with a **transversely polarized target** and measure the transversity distribution function. JLAB12 cover the valence region.

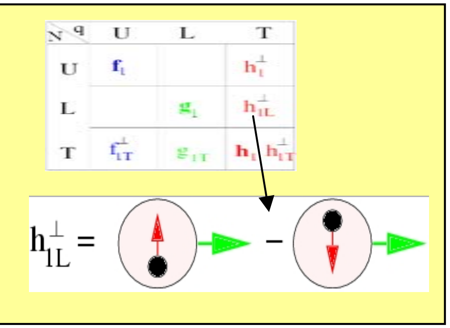
From CLAS12 to EIC: Transversity projections



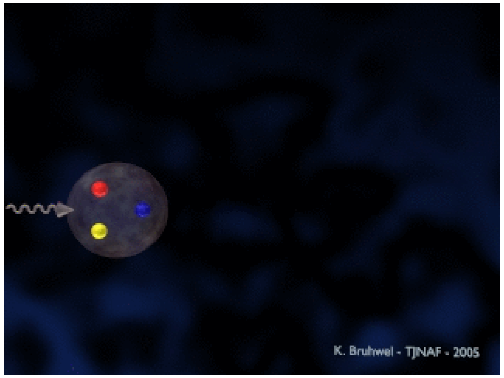
Simultaneous measurement of, exclusive ρ,ρ+,ω with a transversely polarized target

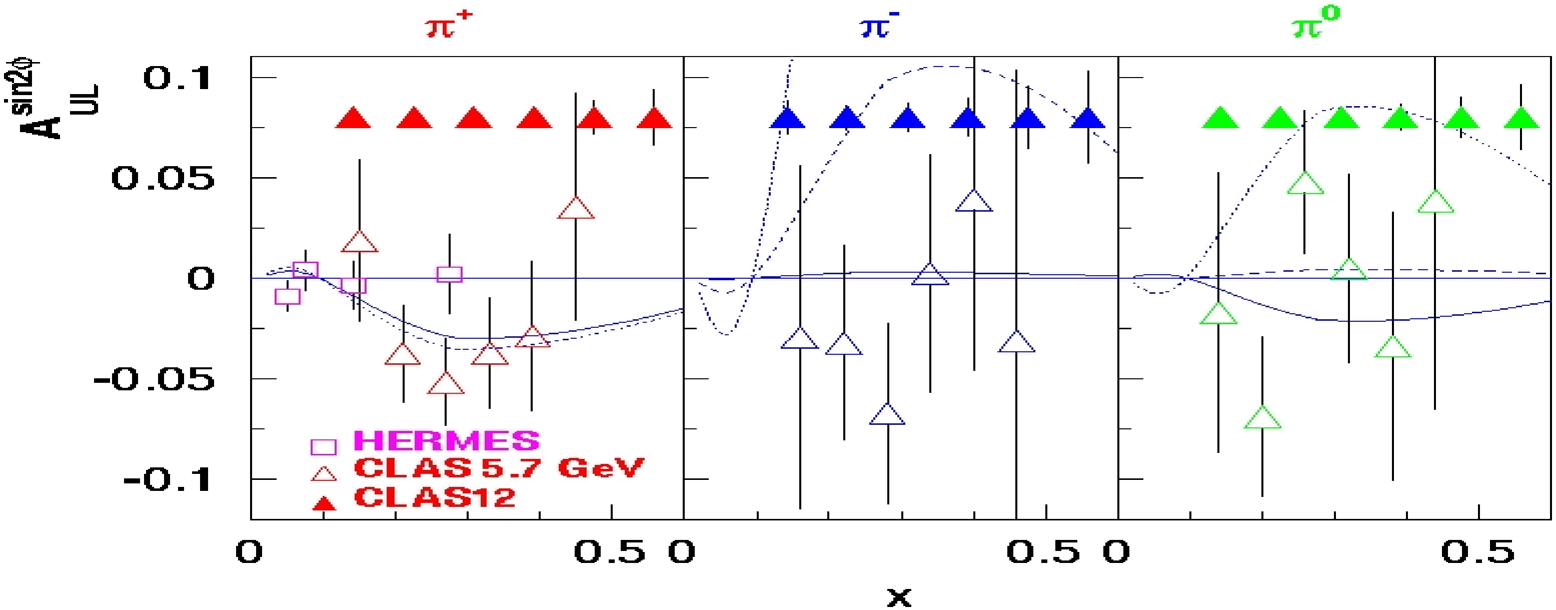
The background from vector mesons very different for CLAS12 and EIC.

Collins Effect and Kotzinian-Mulders Asymmetry



$$\sigma_{UL}^{KM} \sim (1-y) h_{1L}^{\perp} H_1^{\perp}$$

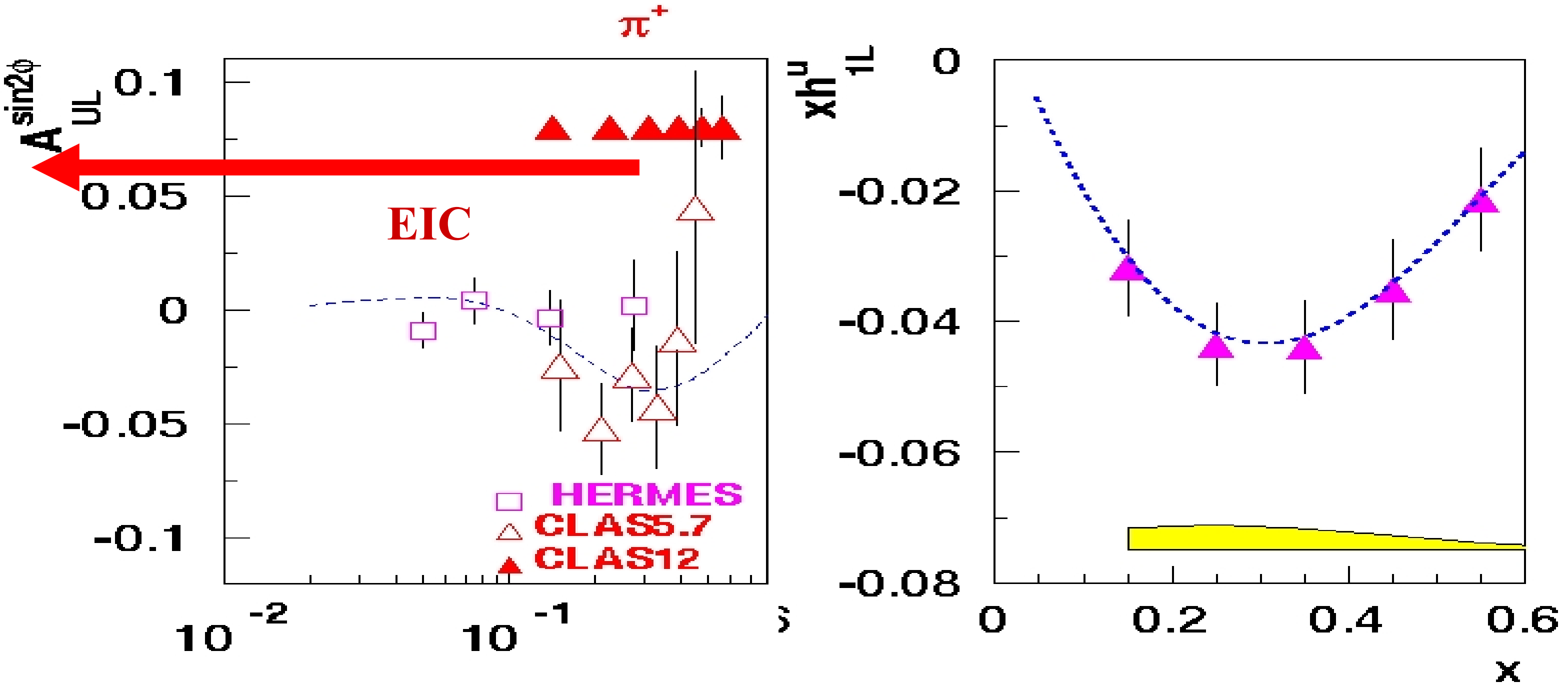




Study the Collins fragmentation with longitudinally polarized target.
Measure the twist-2 Mulders TMD (real part of interference of L=0 and L=1 wave functions)

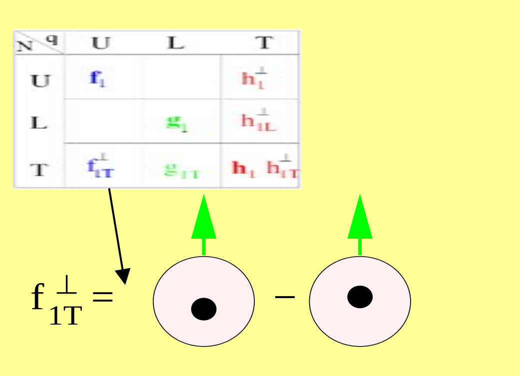
From CLAS12 to EIC: Mulders TMD projections

$$\sigma_{UL}^{KM} \sim (1-y) h_{1L}^{\perp} H_1^{\perp}$$

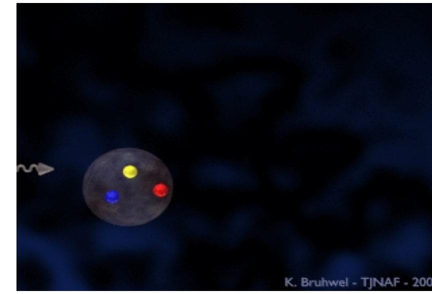


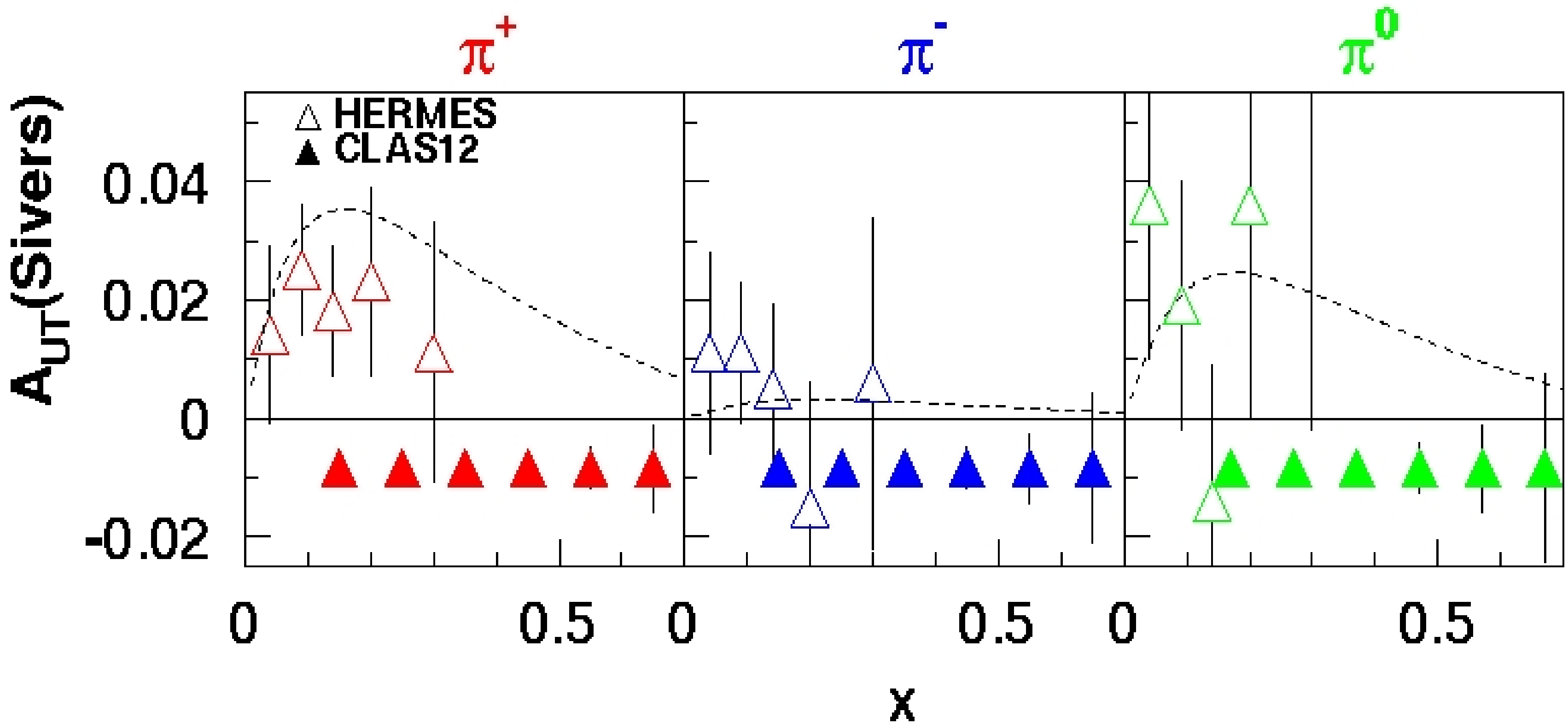
Simultaneous measurement of, exclusive ρ,ρ+,ω with a longitudinally polarized target important to control the background.

Sivers effect



$$\sigma_{UT}^{Sivers} \sim (2-2y+y^2) f_{1T}^{\perp} D_1$$





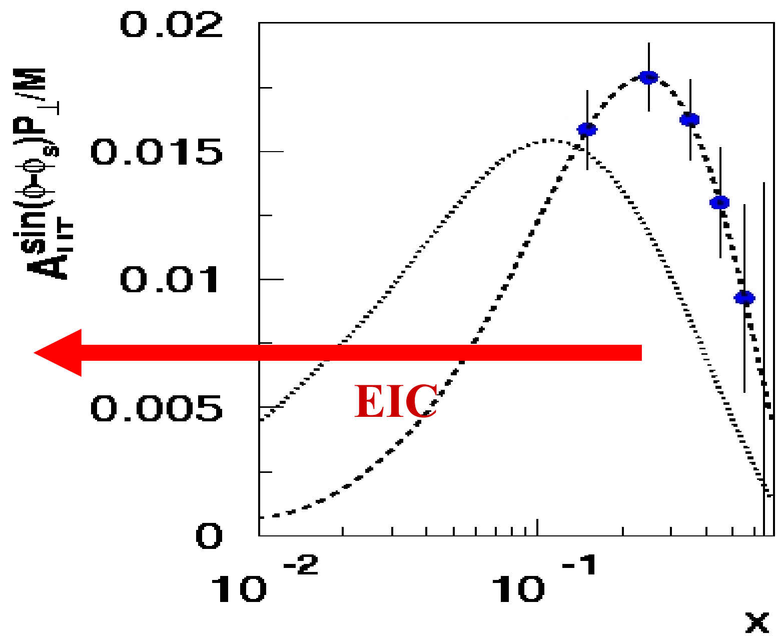
Requires: non-trivial phase from the FSI + interference between different helicity states
Provides: info about the space-time structure of the nucleon

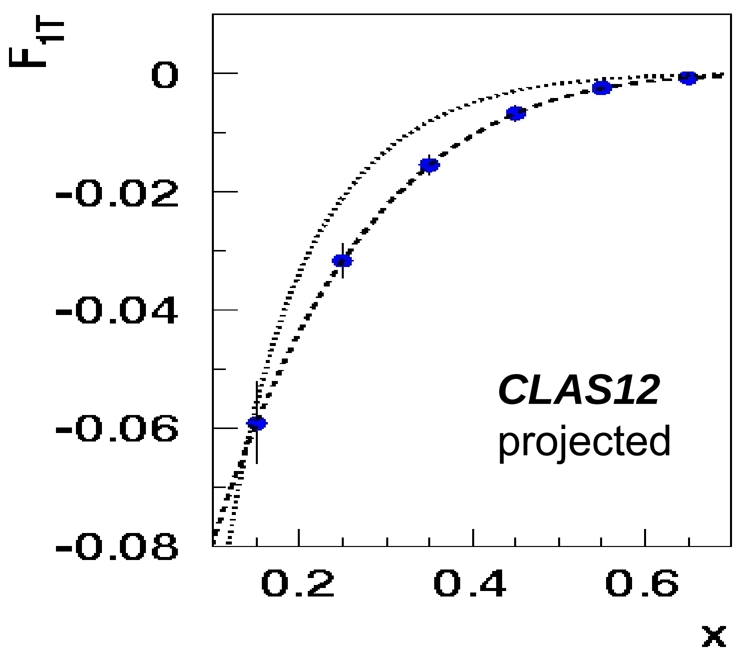
From CLAS12 to EIC: Sivers effect projections

In large Nc limit:
$f_{1T}^{u} = -f_{1T}^{d}$

$F_{1T}=\sum_q e_q^2 f_{1T}^{\perp q}$

Efremov et al
(large x_B behavior of
f_{1T} from GPD E)





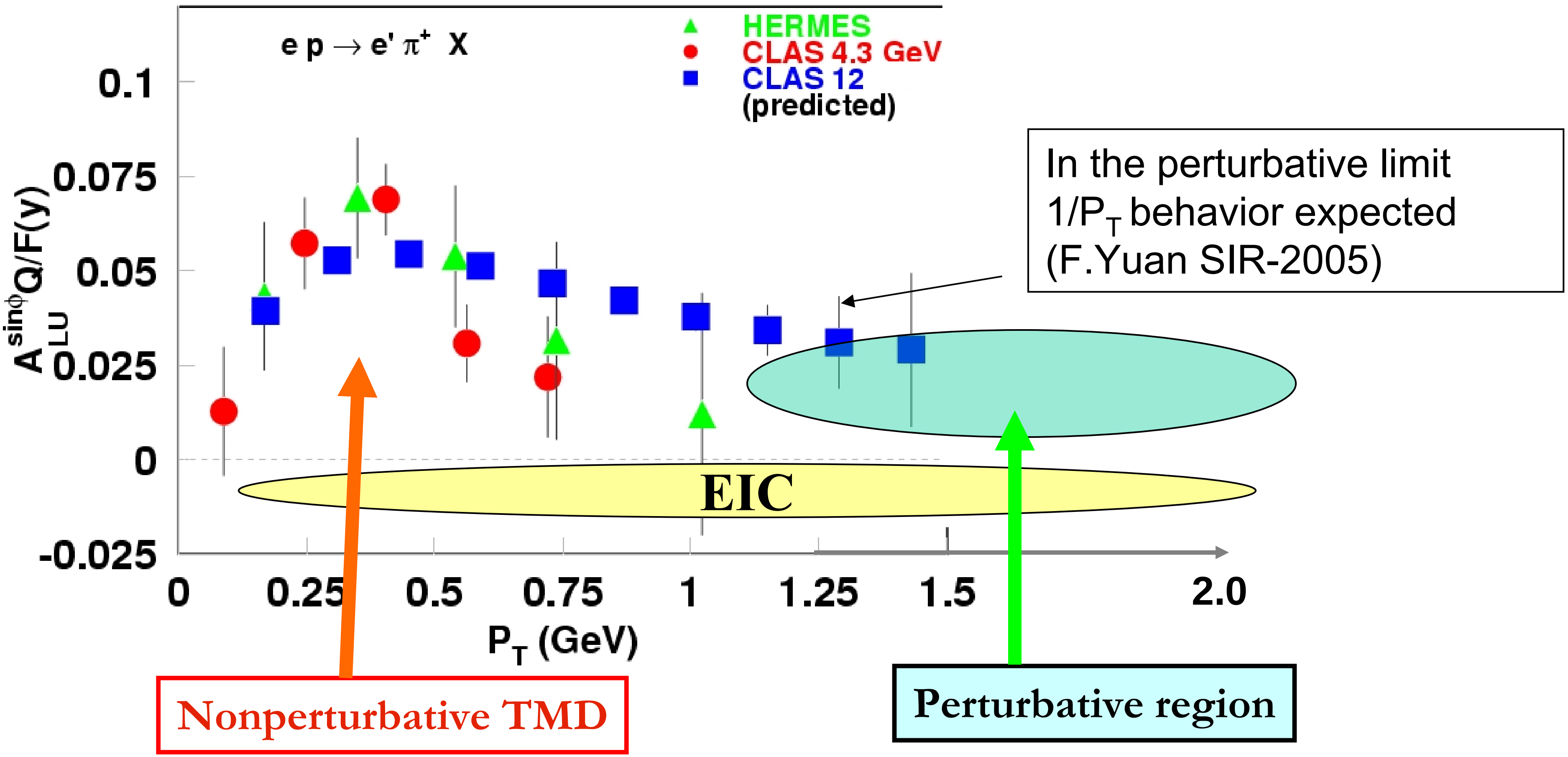
Sivers function extraction from A_{UT} (π^0) does not require information on fragmentation function. It is free of HT and diffractive contributions.

A_{UT} (π^0) on proton and neutron will allow flavor decomposition w/o info on FF.

P_T-dependence of beam SSA

$\sigma^{\sin\phi}_{LU(UL)} \sim F_{LU(UL)} \sim 1/Q$ (Twist-3)

$$A_{LU} \propto g^{\perp(1)}(x) D_1(z)$$



Study for SSA transition from non-perturbative to perturbative regime.
EIC will significantly increase the P_T range.

Flavor decomposition of T-odd $g^{\perp}$

In jet SIDIS with massless quarks contributions from $H_1^{\perp}$,E vanish

$$\sigma_{UU} \propto \left(1 - y + y^2/2\right) \sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z)$$

$$\sigma_{LU}^{\sin\phi} \propto S_L \frac{M}{Q} y\sqrt{1-y} \sum_{q,\bar{q}} e_q^2 x g^{\perp q}(x) D_1^q(z)$$

A_{LU} ($g^{\perp}$) like A_1 (g_1) and Sivers A_{UT} ($f_1^{\perp}$) depend on $D_1(z)$

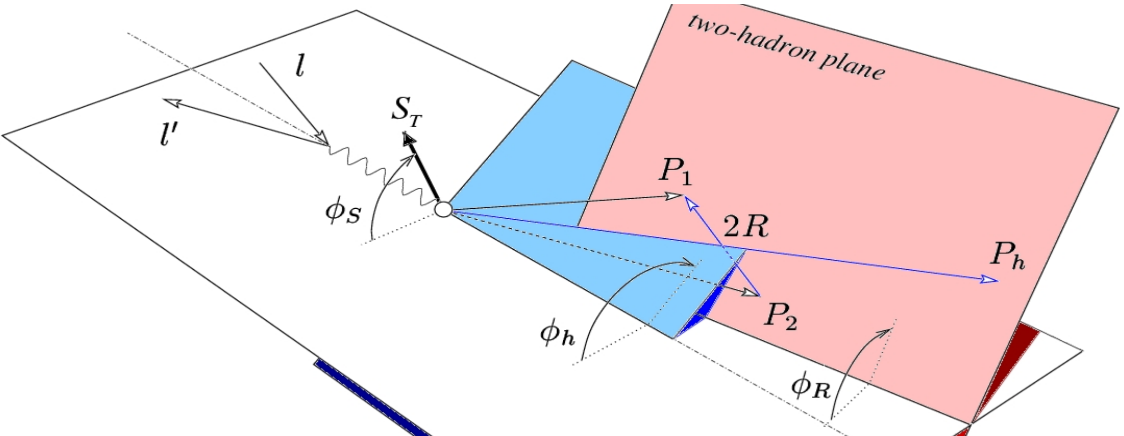
With SSA measurements for π+π– on neutron and proton ($\pi=\pi^0=\pi^+ + \pi^-$)

$$xg^{\perp d}(x) = \tfrac{4}{15}\left[A^{\pi}_{LU,n}\left(4d+u\right) - A^{\pi}_{LU,p}\left(u + d/4\right)\right]$$

$$xg^{\perp u}(x) = \tfrac{4}{15}\left[A^{\pi}_{LU,p}\left(4u+d\right) - A^{\pi}_{LU,n}\left(d + u/4\right)\right]$$

Beam SSA measurements at EIC will allow to study the Q^2 dependence of twist-3 $g^{\perp}$ (generated by gauge link)

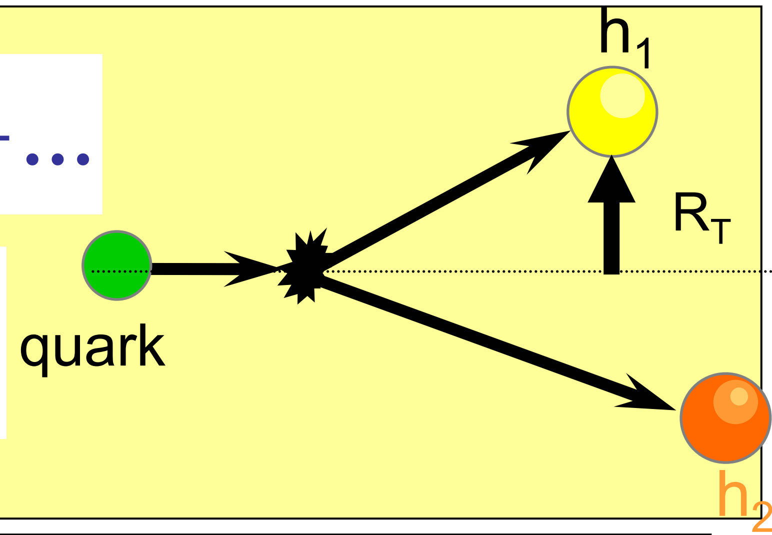
Transversity in double pion production



The angular distribution of two hadrons is sensitive to the spin of the quark

$$A_{UT} \propto \sin(\varphi_R + \varphi_S)\, h_1 H_1^{\perp R} + \ldots$$

"Collinear" dihadron fragmentation described by two functions at leading twist:
$D_1(z,\cos\theta_R,M\pi\pi)$, $H_1^R(z,\cos\theta_R,M\pi\pi)$



Collins et al,
Ji, Jaffe et al,
Radici et al.

relative transverse momentum of the two hadrons replaces the P_T in single-pion production (No transverse momentum of the pair center of mass involved)

Dihadron production provides an alternative, "background free" access to transversity

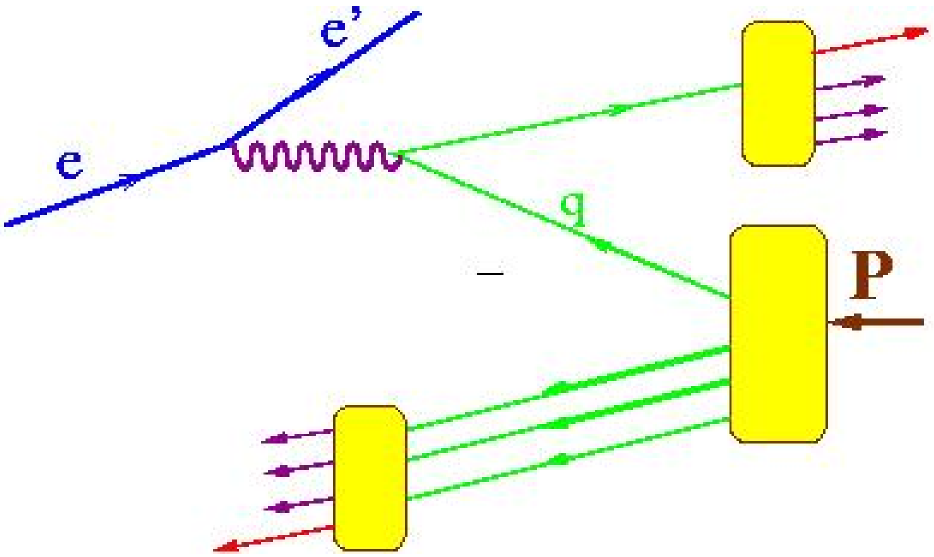
SIDIS: target fragmentation

$$z = \frac{E_h}{\nu}$$

$$x_F = \frac{p_L^*}{p_{L\,max}^*}$$

x_F - momentum in the CM frame

$x_F>0$ (current fragmentation)

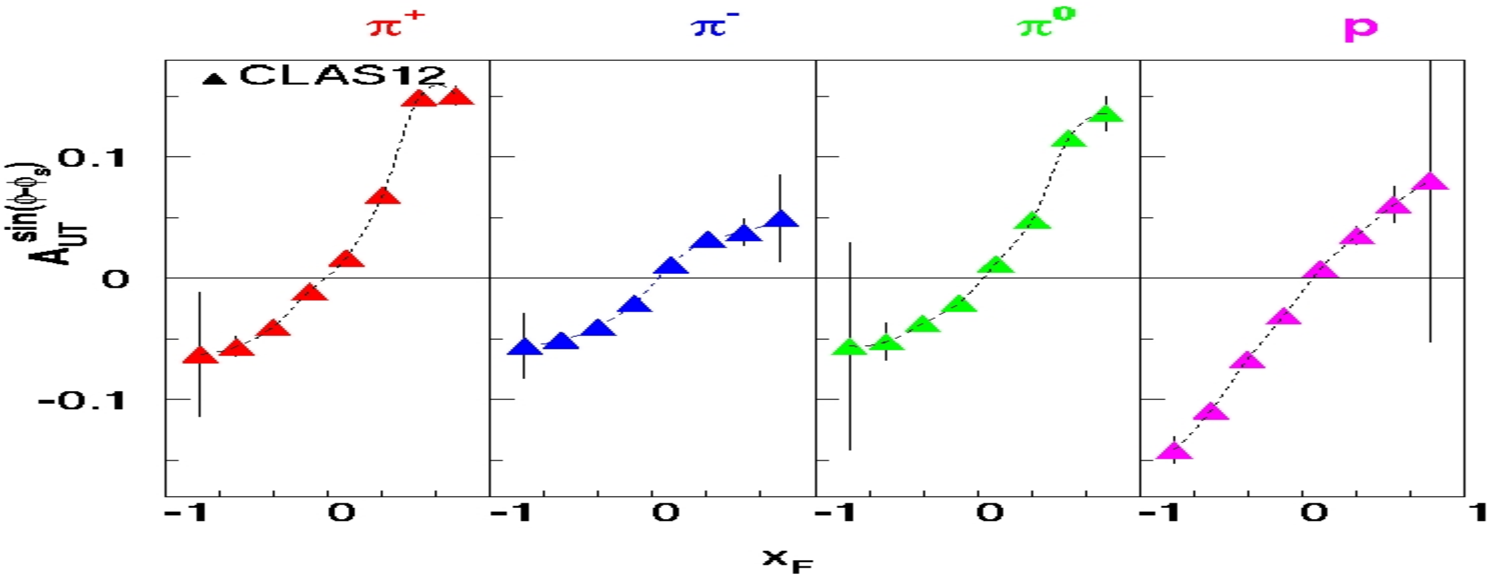


$x_F<0$ (target fragmentation, TFR)

Wide kinematical coverage of a large acceptance detector allows studies of hadronization both in the current and target fragmentation region

Sivers effect in the target fragmentation

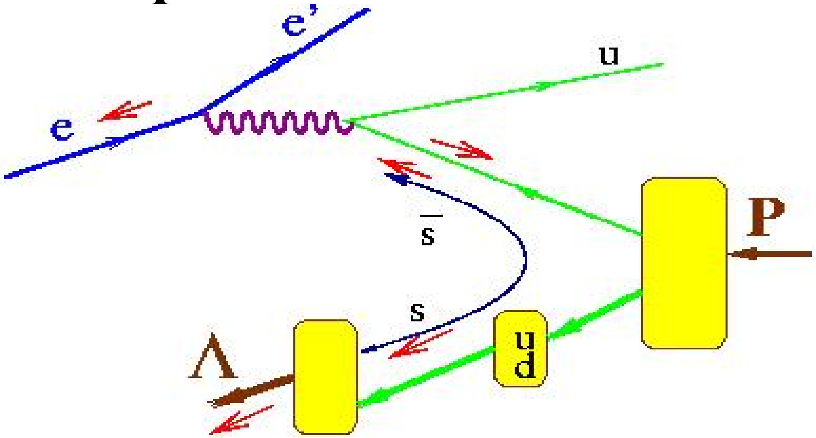
A.Kotzinian

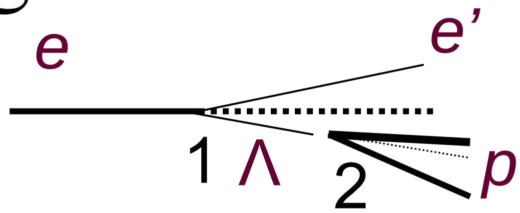


Significant effect predicted in the target fragmentation region, in particular for baryons (target remnant also asymmetric)

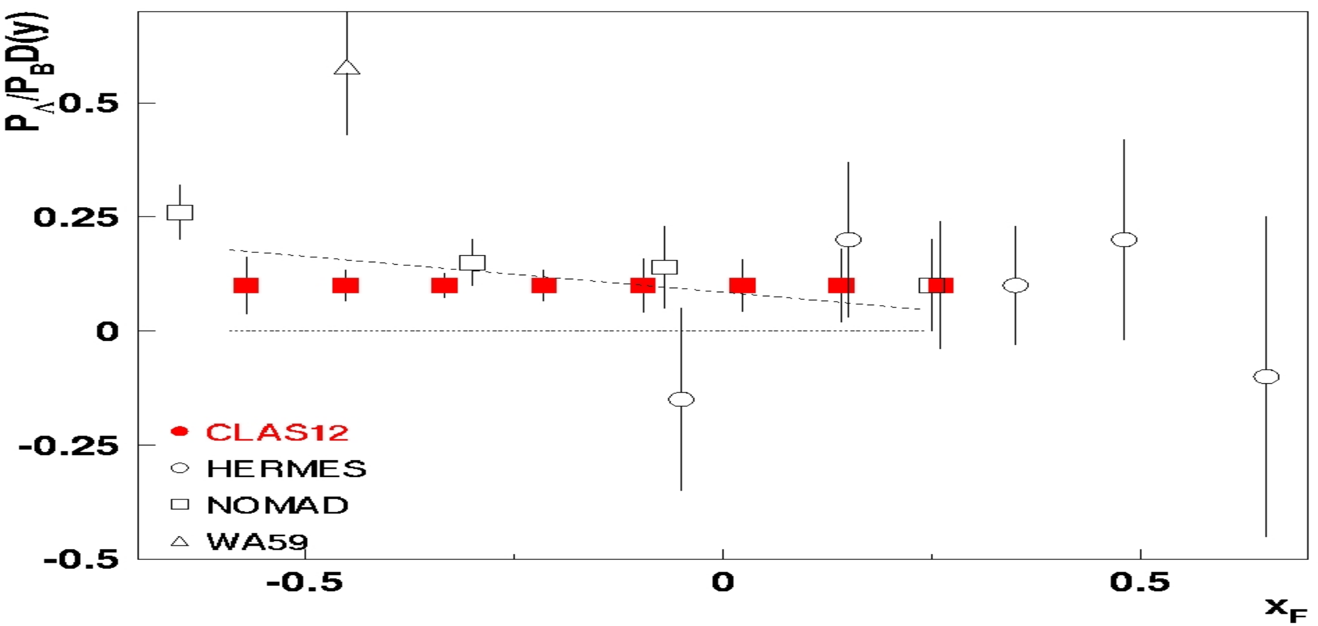
EIC will allow studies of Q^2 dependence of the Sivers effect in the target fragmentation region

Λ polarization in the target fragmentation





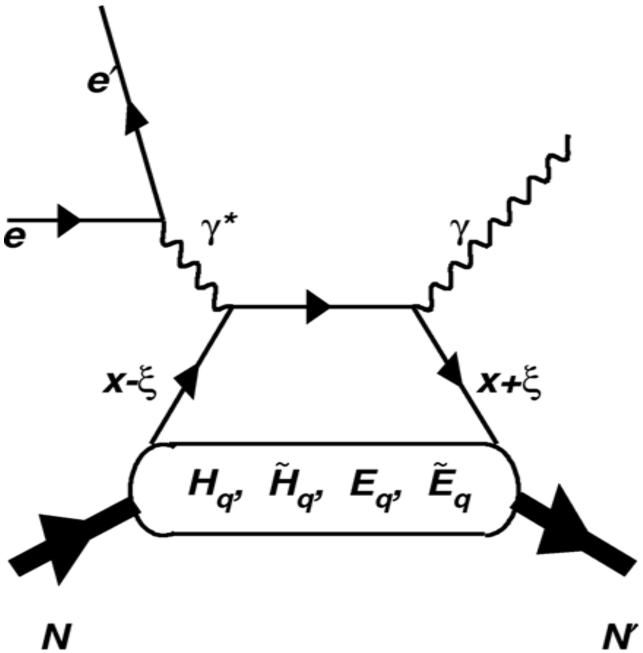
Λ – unique tool for polarization study due to self-analyzing parity violating decay



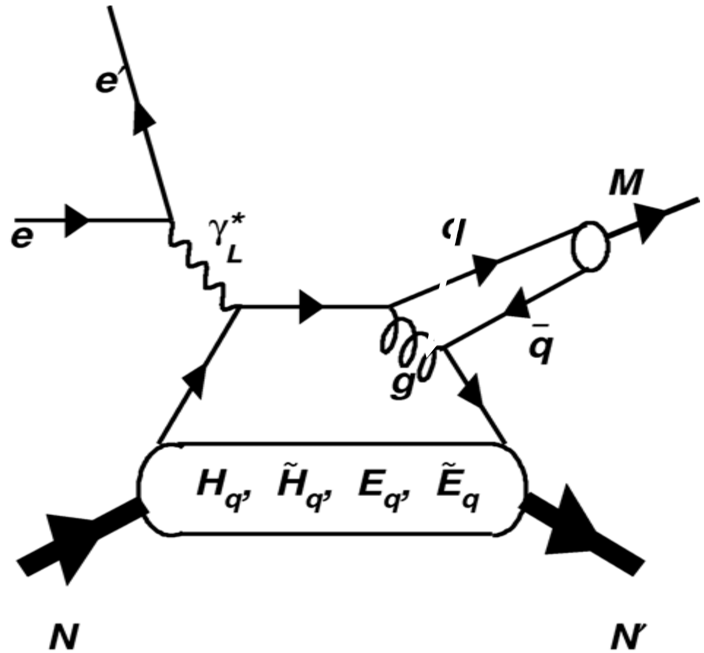
Wide kinematic coverage of CLAS12 allows studies of hadronization in the target fragmentation region

Hard Exclusive Processes and GPDs

DVCS



DVMP



DVCS – for different polarizations of beam and target provide access to different combinations of GPDs H, H, E

DVMP for different mesons is sensitive to flavor contributions (ρ^0/ρ^+ select H, E, for u/d flavors, π, η, K select H, E)

Separating GPDs through polarization

$ep \longrightarrow ep\gamma$

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

$\xi = x_B/(2-x_B)$
$k = t/4M^2$

Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi$$

Kinematically suppressed

$\Rightarrow$ $\mathbf{H}$, $\tilde{H}$, E

Unpolarized beam, longitudinal target:

$$\Delta\sigma_{UL} \sim \sin\phi\{F_1\tilde{H} + \xi(F_1+F_2)(H + \ldots\}d\phi$$

$\Rightarrow$ H, $\tilde{\mathbf{H}}$

Unpolarized beam, transverse target:

$$\Delta\sigma_{UT} \sim \sin\phi\{k(F_2 H - F_1 E) + \ldots..\}d\phi$$

$\Rightarrow$ $\mathbf{H}$, $\mathbf{E}$

CLAS12 - DVCS/BH Beam Asymmetry

$\vec{e}\,p \longrightarrow ep\gamma$

E = 11 GeV

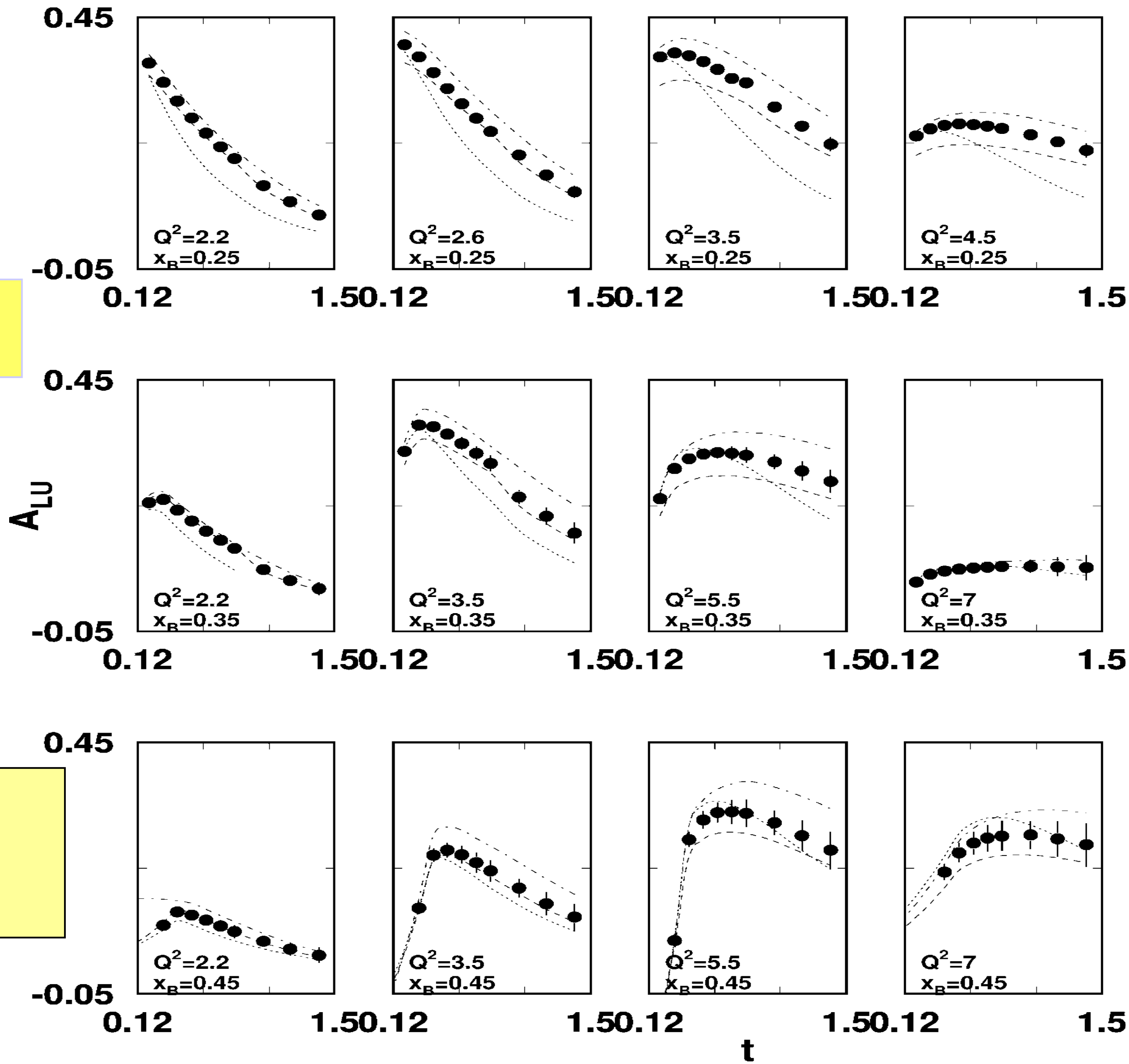
$\Delta\sigma_{LU} \sim \sin\phi \, \mathrm{Im}\{F_1 \mathcal{H} + ..\} d\phi$

Sensitive to GPD H

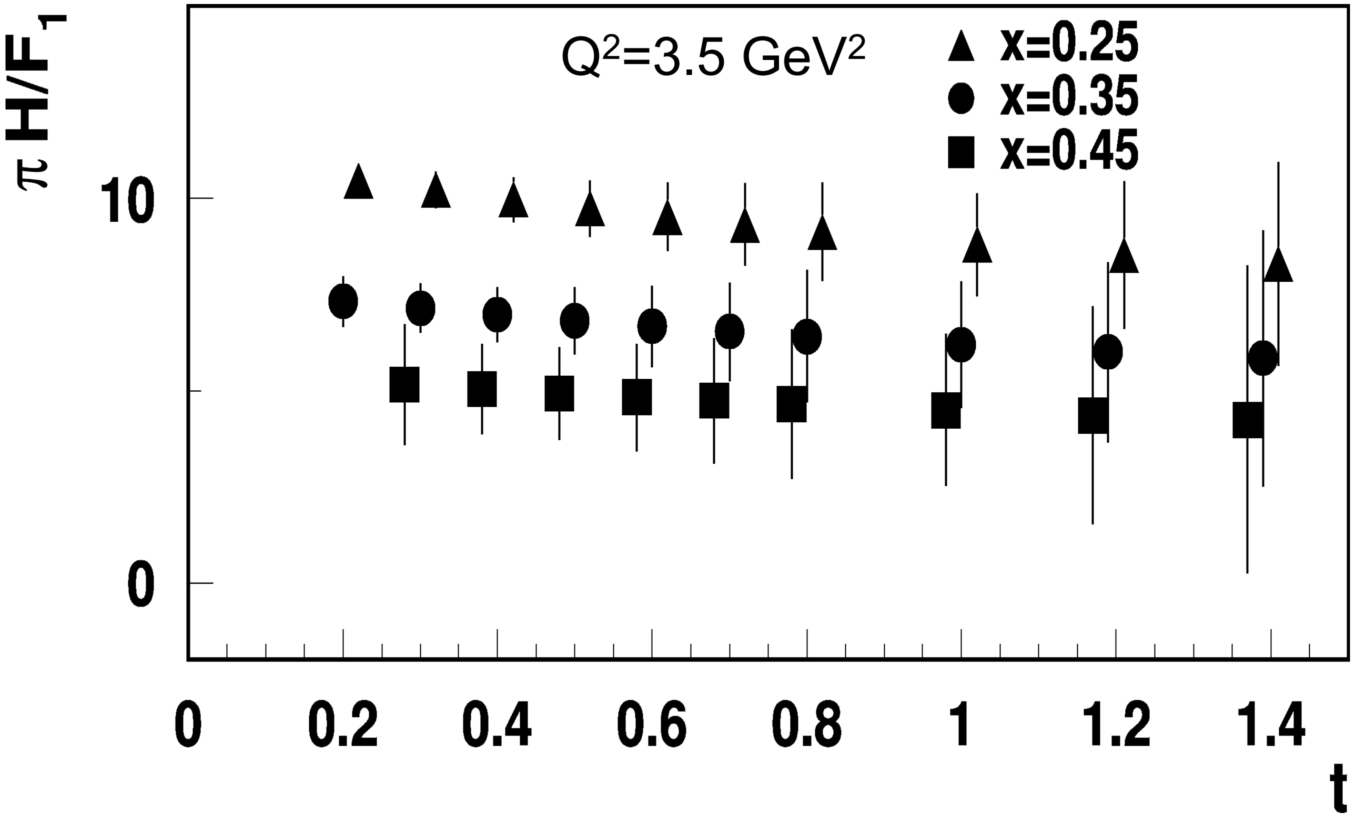
Selected Kinematics

$L = 1\times10^{35}$
$T = 2000$ hrs
$\Delta Q^2 = 1$ GeV^2
$\Delta x = 0.05$

Acceptance of protons for EIC studied using Roman Pots (60% efficiency)



GPDs H from expected DVCS A_{LU} data



$b_{val}=b_{sea}=1$

MRST02 NNLO distribution

- Other kinematics measured concurrently

CLAS12 – DVCS/BH Target Asymmetry

$$e\,\vec{p} \longrightarrow ep\gamma$$

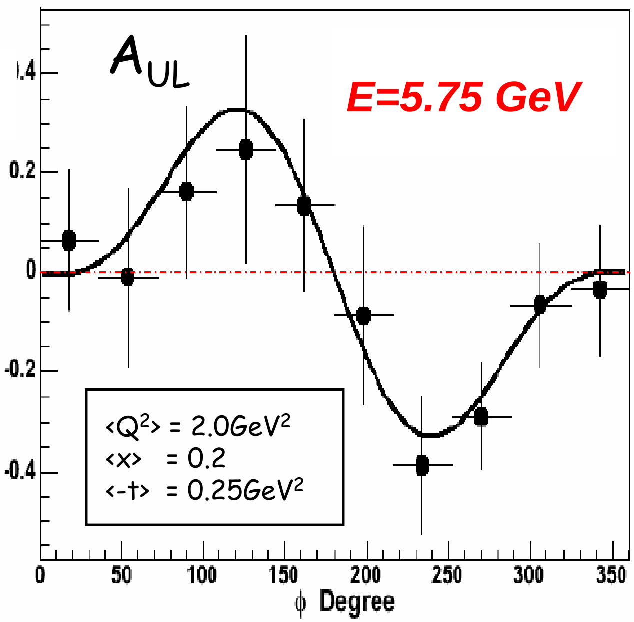
E = 11 GeV

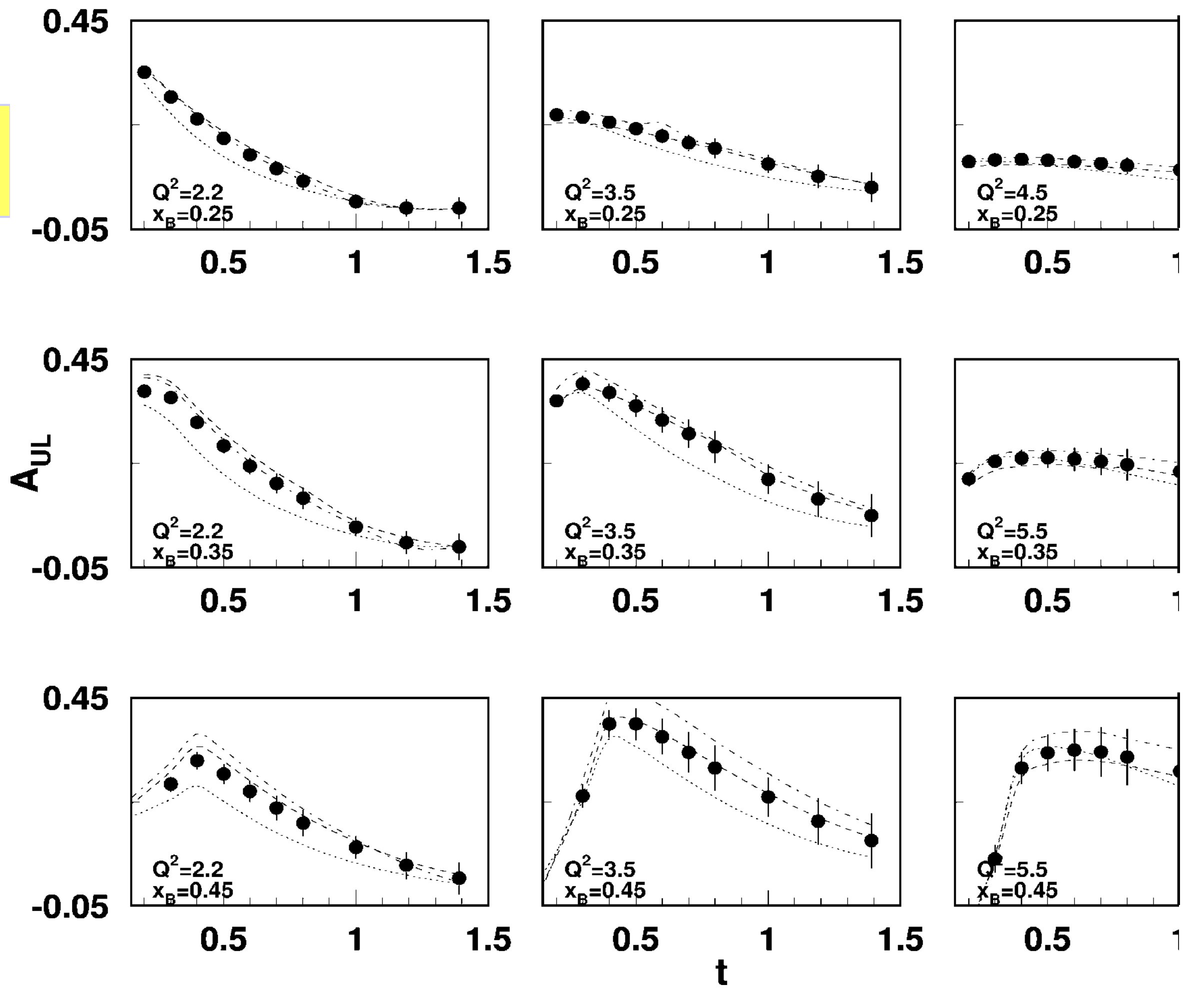
$L = 2\times10^{35}\ \mathrm{cm^{-2}s^{-1}}$
$T = 1000$ hrs
$\Delta Q^2 = 1\mathrm{GeV}^2$
$\Delta x = 0.05$

Longitudinally polarized target

$$\Delta\sigma \sim \sin\phi\, \mathrm{Im}\{F_1\tilde{H} + \xi(F_1+F_2)H \ldots\}d\phi$$

CLAS preliminary





CLAS12 - DVCS/BH Target Asymmetry

$e\, p^{\uparrow} \longrightarrow e p \gamma$

E = 11 GeV

Sample kinematics

Q^2=2.2 GeV^2, x_B = 0.25, -t = 0.5GeV^2

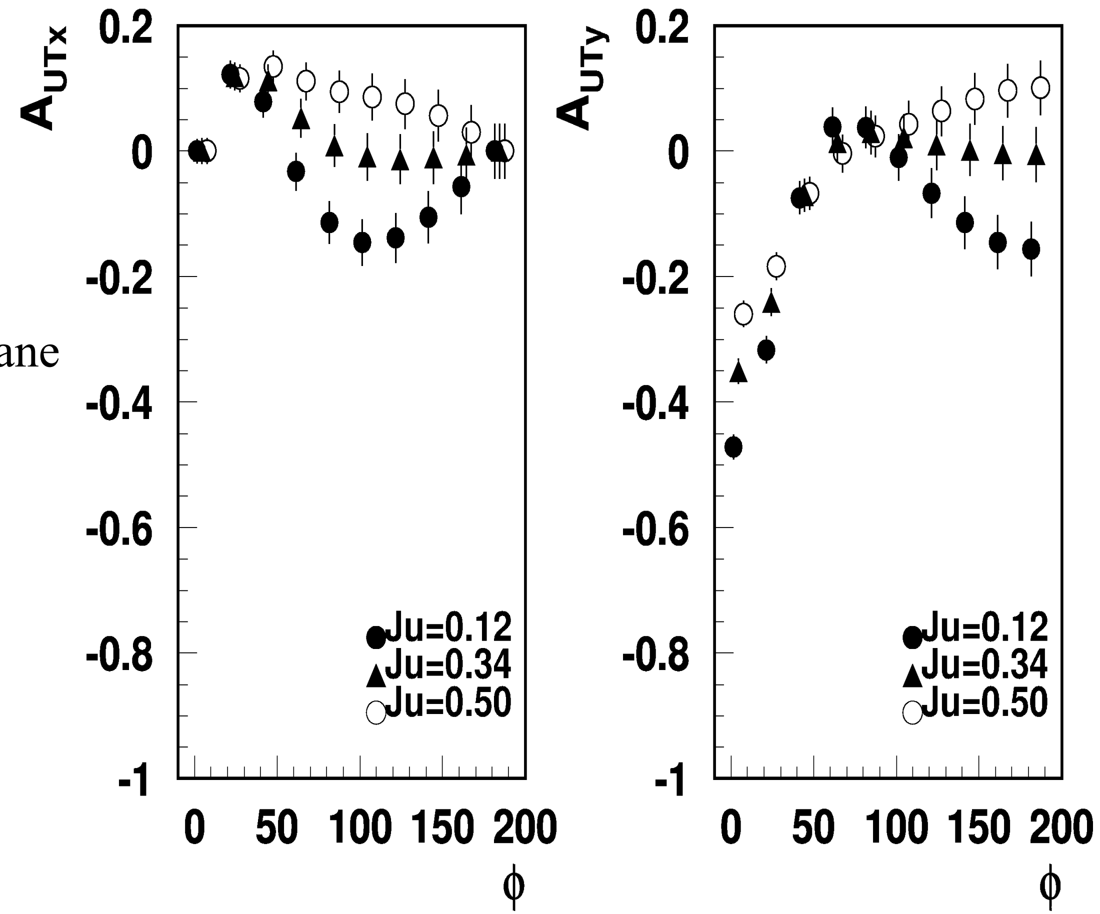
Transverse polarized target

$$\Delta\sigma \sim \sin\phi \,\mathrm{Im}\{k_1(F_2 H - F_1 E) + \ldots\}d\phi$$

A_{UTx} Target polarization in scattering plane

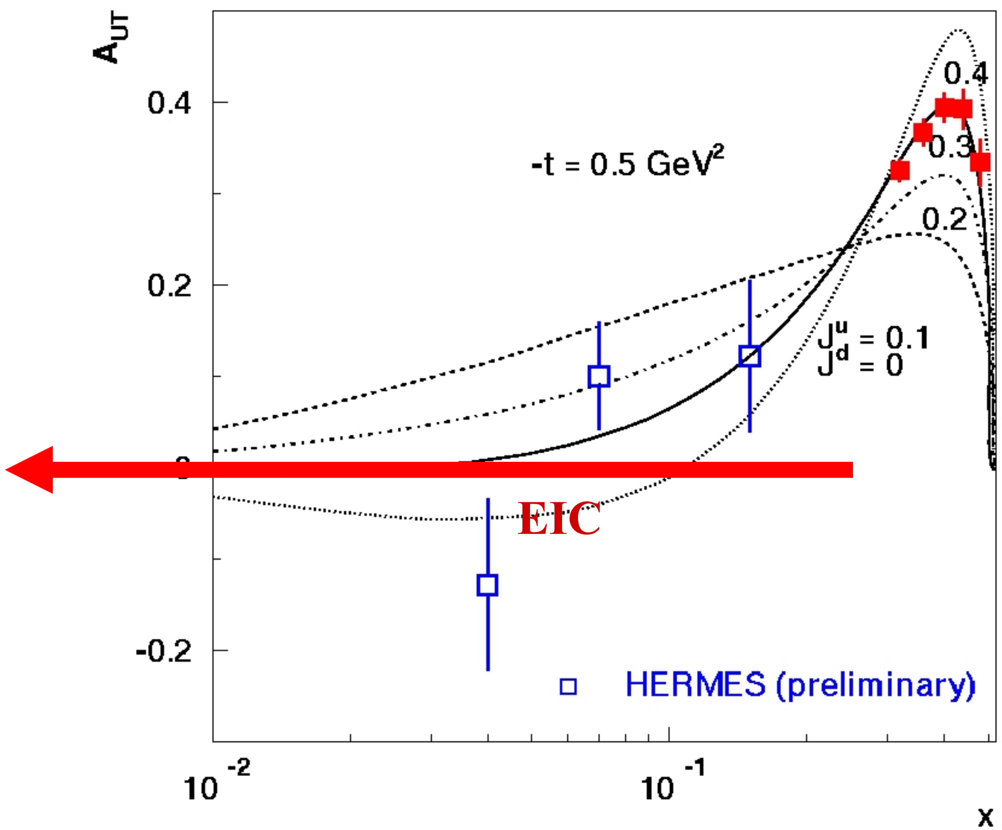
A_{UTy} Target polarization perpedicular to scattering plane

- Asymmetry highly sensitive to the u-quark contributions to proton spin.



Exclusive ρ^0 production on transverse target

$$A_{UT} = -\frac{2\Delta_\perp(\mathrm{Im}(AB^*))/\pi}{|A|^2(1-\xi^2) - |B|^2(\xi^2+t/4m^2) - \mathrm{Re}(AB^*)2\xi^2}$$



ρ^0: $A \sim 2H^u + H^d$, $B \sim 2E^u + E^d$

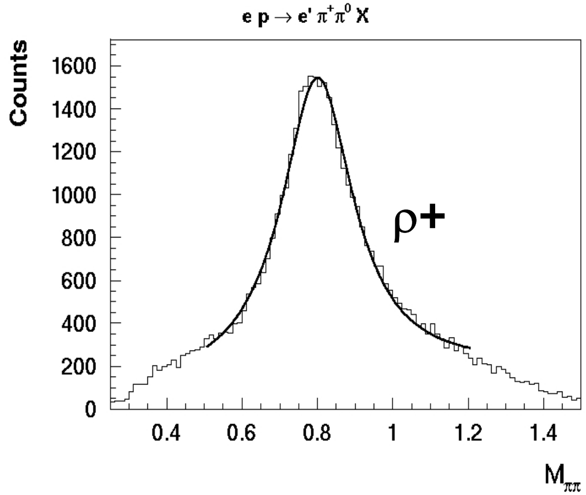
ρ^+: $A \sim H^u - H^d$, $B \sim E^u - E^d$

E^u, E^d needed for angular momentum sum rule.

Higher Q^2 of EIC may be crucial

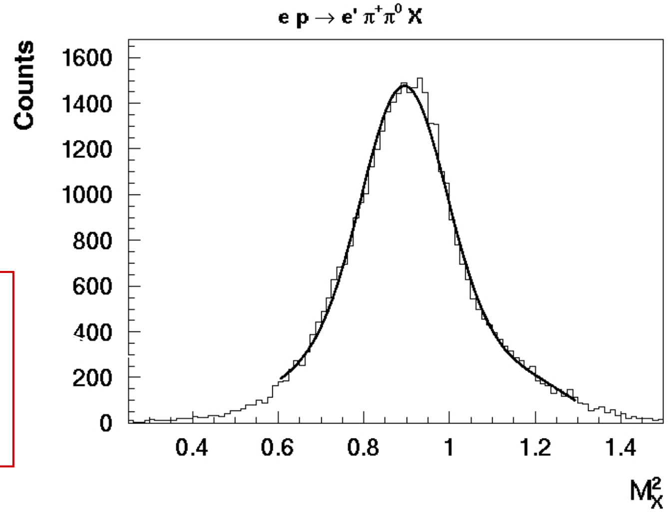
Exclusive ρ+ production

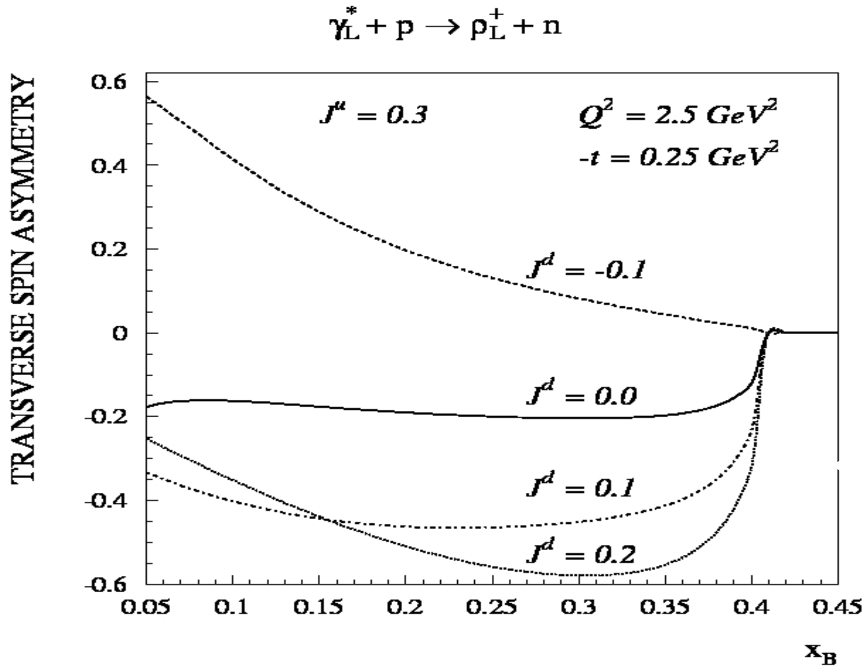
$e^- p \rightarrow e^- n\rho^+$, $\rho^+ \rightarrow \pi^+\pi^0$



Exclusive ρ+n separated by invariant and missing masses.

Doesn't require detection of recoil nucleon





Provide access to different combinations of orbital momentum contributions J^u,J^d

ρ^0 -> $2J^u + J^d$

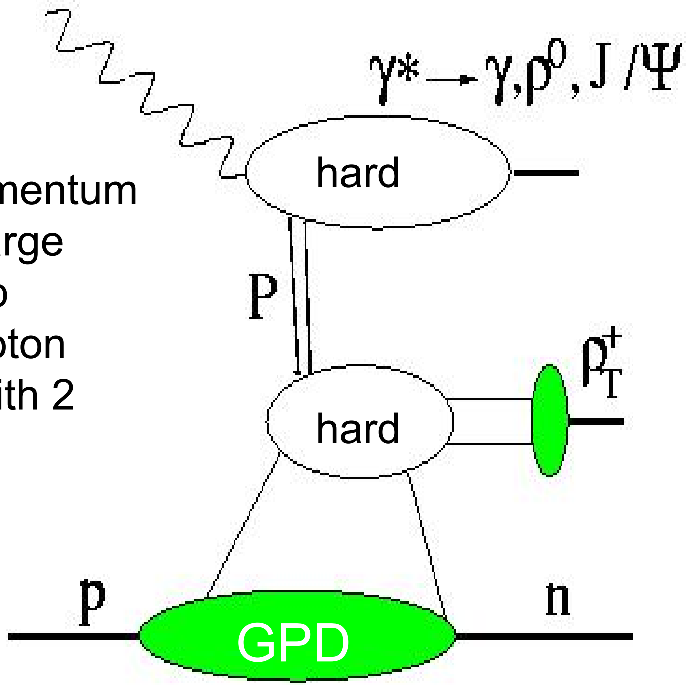
ρ^+ -> $J^u - J^d$

ω -> $2J^u - J^d$

- Significant transverse target SSA predicted also for exclusive ρ^+ (Goeke et al hep-ph/0106012)

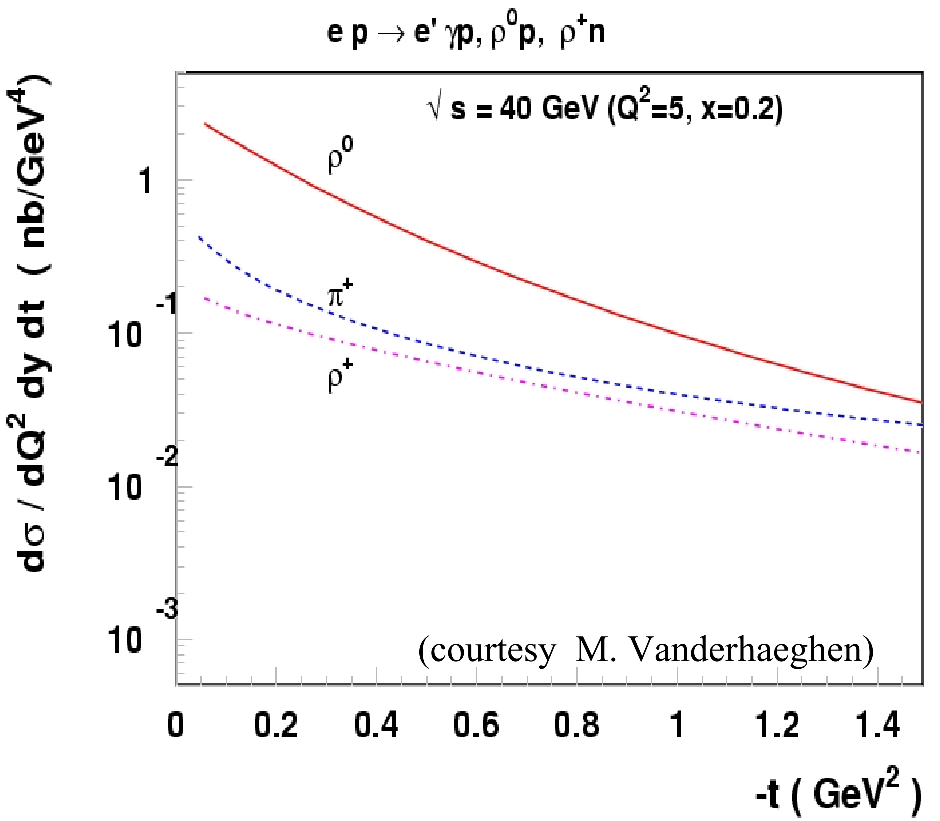
Transversity GPDs with exclusive $\rho, \rho+$

$$\gamma^* N \to \rho_L^0 \rho_T^+ N'$$



- Large momentum transfer, large rapidity gap
- Virtual photon replaced with 2 gluons

Long distance part described by GPD H_T



Smaller rapidity gap
$\rho+$ selects quark antiquark exchange with the nucleon.

Ivanov et al. **Phys.Part.Nucl.35:S67-S70,2004**

Summary

- *CLAS12* a full acceptance, general purpose detector for high luminosity electron scattering experiments, is essential for high precision measurements of GPDs and TMDs in the valence region.
  - Provide new insight into
    - quark orbital angular momentum contributions to the nucleon spin
    - 3D structure of the nucleon's interior and correlations
    - quark flavor polarization

- *EIC* will extend studies of 3D nucleon structure, to low $\boldsymbol{x}$ and high $\boldsymbol{Q^2}$, important for all processes of interest:
  - deeply virtual exclusive processes (DVCS, DVMP)
  - semi-inclusive meson production with polarized beam and polarized targets